Efficient GaInAsSb/AlGaAsSb diode lasers emitting at 2.29 μm

S. J. Eglash and H. K. Choi
Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts 02173-9108

(Received 2 May 1990; accepted for publication 21 July 1990)

Diode lasers emitting at 2.29 μm have been fabricated from lattice-matched double heterostructures having a GaInAsSb active layer and AlGaAsSb confining layers grown by molecular beam epitaxy on GaSb substrates. For pulsed room-temperature operation these devices have exhibited threshold current densities as low as 1.7 kA/cm^2 and differential quantum efficiencies as high as 18% per facet, the highest room-temperature efficiency reported for any semiconductor diode laser emitting beyond 2 μm.

High performance semiconductor diode lasers with emission wavelengths λ in the range 2–5 μm would be useful for a variety of applications, including optical communications employing low-loss fluoride-based fibers, laser radar exploiting atmospheric transmission windows, remote sensing of atmospheric gases, and molecular spectroscopy. Diode lasers incorporating GaInAsSb active layers and AlGaAsSb confining layers lattice matched to GaSb substrates can potentially provide room-temperature emission from 1.7 to 4.4 μm (Ref. 1) with good carrier and optical confinement.

Room-temperature cw operation with $\lambda = 2.0$–2.3 μm has been reported[2,3] for GaInAsSb/AlGaAsSb double-heterostructure lasers grown by liquid phase epitaxy (LPE). Pulsed threshold current densities J_{th} as low as 1.5 kA/cm^2 have been obtained for such devices.[2] Molecular beam epitaxy (MBE) has also been used to grow GaInAsSb/AlGaAsSb double heterostructures, but the lowest J_{th} value reported[4] for lasers fabricated from MBE-grown material is 4.2 kA/cm^2.

In this study we have used MBE to grow lattice-matched GaInAsSb/AlGaAsSb double-heterostructure lasers with $\lambda = 2.29$ μm, J_{th} as low as 1.7 kA/cm^2, and differential quantum efficiencies η_d as high as 18% per facet. This J_{th} value is almost as low as the best value reported for LPE-grown devices. Our η_d values are much greater than the best reported[3,5] for any GaInAsSb/AlGaAsSb laser, and are thus the highest so far obtained for room-temperature operation of any semiconductor diode laser emitting beyond 2 μm.

Commercial Te-doped n-GaSb (100) substrates were used for growth of the laser structures. The substrate was etched to remove contaminants and surface damage, mounted with In onto a 75 mm holder, loaded into a Varian Gen II MBE system, and heated in the presence of an Sb flux to desorb surface oxides and other contaminants. Reflection high-energy electron diffraction patterns revealed the 3×1 reconstruction that is characteristic of Sb-stabilized GaSb (100) surfaces and showed the substrate to be clean and atomically smooth.

The sources used for MBE growth were the group III and group V elements, which yielded beams of Al, Ga, and In atoms and of As_4 and Sb_4 molecules. The substrate temperatures and V:III flux ratios employed for epilayer growth were optimized to yield the best surface morphology. The efficiency of incorporation is near unity for Sb as well as for the group III elements. Arsenic is incorporated much less readily than Sb because, in comparison with Sb_4, As_4 has a shorter surface residence time [heat of sublimation of 37 kcal/mol for As_4 vs 49 kcal/mol for Sb_4 (Ref. 6)] and is more stable [atomization energy of 252 kcal/mol for As_4 vs 203 kcal/mol for Sb_4 (Ref. 6)]. Therefore, the As and Sb mole fractions in the GaInAsSb and AlGaAsSb layers were controlled by using a large excess As_4 flux and reducing the Sb:III ratio far enough below 1 to yield the desired Sb mole fraction. The impurity used for n-type doping was Te provided by the sublimation of GaTe.[7] The p-type dopant was Be, which is conventionally used in the MBE growth of III-V materials. Using these dopants we have obtained carrier concentrations as high as 1×10^{18} and 1×10^{17} cm^{-3} in n-type GaSb and AlGaAsSb, respectively, and 2×10^{18} and 1×10^{18} cm^{-3} in p-type GaSb and AlGaAsSb, respectively.

Figure 1 shows a schematic diagram and scanning electron micrograph of a cleaved cross section of a GaInAsSb/AlGaAsSb laser structure, which consists of an n-GaSb (100) substrate, an n^+-GaSb buffer layer, a 1.7-μm-thick n-$Al_{0.50}Ga_{0.50}As_{0.04}Sb_{0.96}$ confining layer, a 0.4-μm-thick nominally undoped $Ga_{0.84}In_{0.16}As_{0.14}Sb_{0.86}$ active layer, a 3.3-μm-thick p-$Al_{0.50}Ga_{0.50}As_{0.04}Sb_{0.96}$ confining layer, and a p^+-GaSb contacting layer. To fabricate broad-stripe lasers, 100- or 300-μm-wide Cr/Au stripes were defined on the p^+-GaSb surface of the wafer by using photoresist lift-off. The p^+ GaSb between the Cr/Au stripes was removed by etching in H_2SO_4:H_2O_2:H_2O to reduce current spreading. The wafer was lapped from the substrate side to 100 μm thickness, and the n-GaSb surface was metallized with Au/Sn. Alloying was performed at 300 °C to reduce the resistance of the Au/Sn contacts to acceptable values. The wafer was cleaved into 300 μm bars, which were then separated into individual lasers by scribing. Both facets were left uncoated.

Figure 2 shows the light output versus current for a 300×300 μm laser measured at room temperature with 1 μs pulses. For this device, $J_{th} = 1.7$ kA/cm^2 and $\eta_d = 15\%$ per facet. Other devices have exhibited η_d values as high as 18% per facet. We have obtained power outputs as high as 290 mW per facet, limited by the power supply used for the measurement. The emission spectrum of a laser 100 μm wide and 300 μm long is shown in Fig. 3. The output is

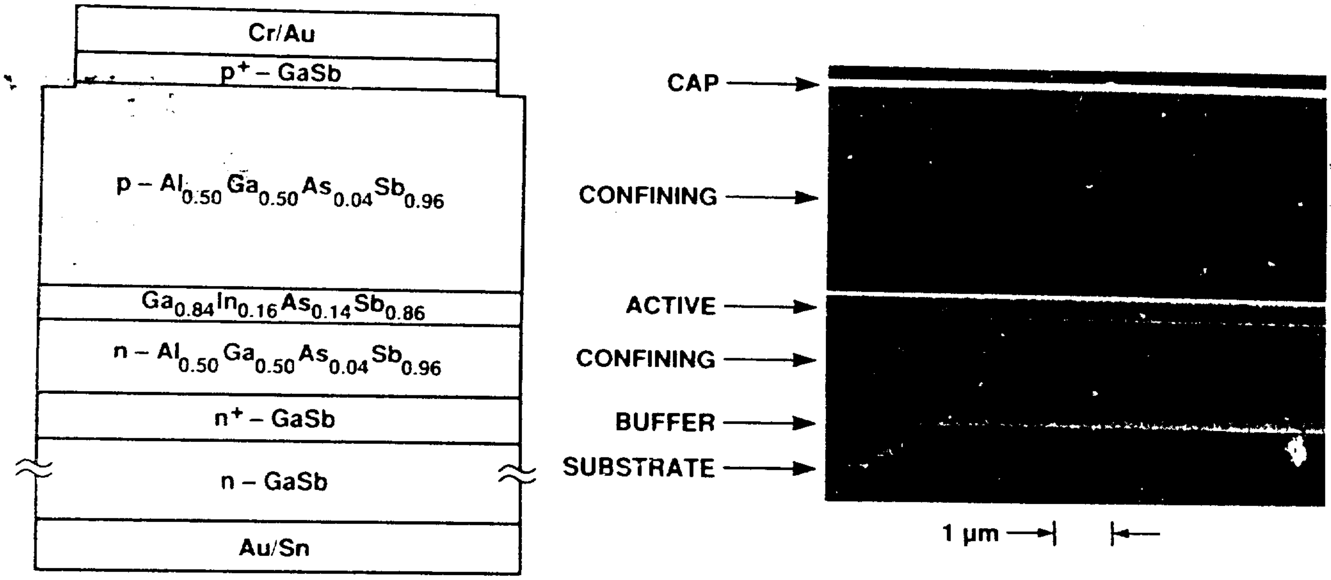

FIG. 1. Schematic diagram and scanning electron micrograph of a cleaved cross section of a GaInAsSb/AlGaAsSb laser structure.

centered at $\lambda = 2.29$ μm. Very similar characteristics were measured for lasers fabricated from two wafers with nominally the same structure that were grown on consecutive days.

Light output versus current curves were measured at temperatures from –120 to 20 °C for another 300×300 μm laser. We obtained $J_{th} = 190$ A/cm^2 at -120 °C. Applying the expression $J_{th}(T) = J_0 \exp(T/T_0)$, where T is the absolute temperature and J_0 and T_0 are empirical parameters,[8] gives T_0 values of 75 and 50 K near -120 and 20 °C, respectively. These values are comparable to the best that have been reported for similar lasers.[2,5,9]

Losses due to nonradiative recombination resulting from Auger transitions have been analyzed theoretically by Sugimura[10] for III-V diode lasers with active layers having band gaps corresponding to emission wavelengths beyond 1 μm. For GaInAsSb/AlGaAsSb lasers emitting at 2.3 μm, he found the dominant Auger loss mechanism to be the CHCC process, in which the energy released by recombination of a conduction-band electron with a heavy hole is transferred to a second conduction-band electron. According to Sugimura's calculations, $J_{th} = 13$ kA/cm^2 at room temperature for devices with an active layer thickness of 0.4 μm. Since this value is far higher than those measured for such lasers both in this study and elsewhere,[2,9] it appears that Sugimura greatly overestimated the transition rate for the CHCC process.

In conclusion, we have used MBE to grow lattice-matched $Ga_{0.84}In_{0.16}As_{0.14}Sb_{0.86}/Al_{0.50}Ga_{0.50}As_{0.04}Sb_{0.96}$ double heterostructures on GaSb substrates. Diode lasers fabricated from these structures have exhibited J_{th} values as low as 1.7 kA/cm^2 and η_d values as high as 18% per facet for room-temperature pulsed operation with $\lambda = 2.29$ μm. Optimization of the laser structure, particularly of active layer thickness and confining layer composition, as

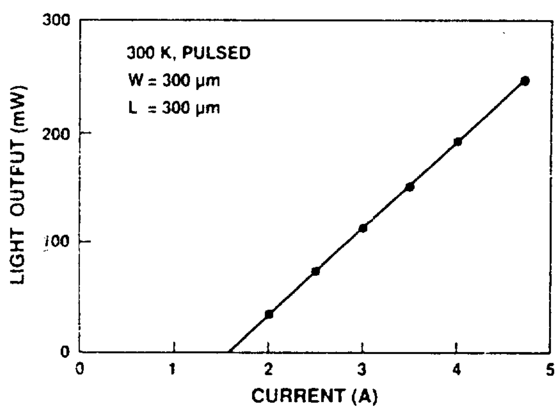

FIG. 2. Light output vs current for pulsed operation of GaInAsSb/AlGaAsSb diode laser at room temperature. Light output measured from one facet; both facets are uncoated. For this device, $J_{th} = 1.7$ kA/cm^2 and $\eta_d = 15\%$ per facet.

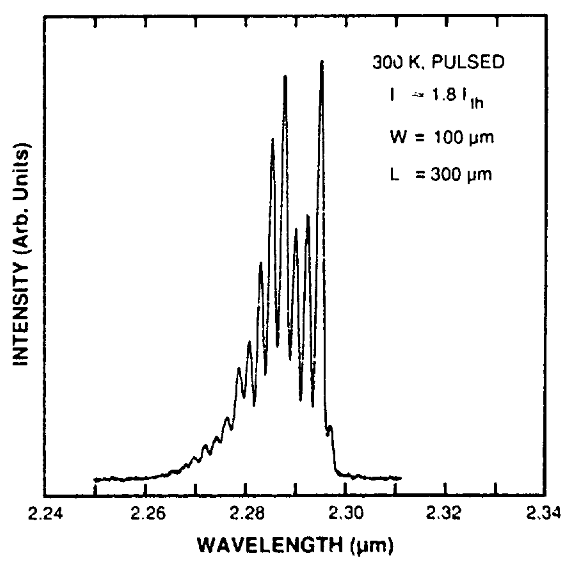

FIG. 3. Emission spectrum of a GaInAsSb/AlGaAsSb diode laser for pulsed operation at room temperature.

well as further development of the MBE growth technique and device processing procedures, can be expected to result in improvements in performance. In addition, it should be possible to extend the emission to significantly longer wavelengths by using MBE to grow the same basic structure, but changing the composition of the GaInAsSb active layer to reduce the energy gap. Because of a miscibility gap in the GaInAsSb system,[11,12] it is unlikely that LPE can be used to grow GaInAsSb-based structures emitting from 2.5 to 4.2 μm.

We are grateful to G. W. Turner for laser emission spectroscopy, P. M. Nitishin for scanning electron microscopy, M. C. Finn for Auger spectroscopy, D. R. Calawa, J. W. Chludzinski, D. F. Kolesar, W. L. McGilvary, K. A. McIntosh, and J. V. Pantano for expert technical assistance, and L. R. Dawson, S. H. Groves, L. Lassabatere, J. N. Walpole, and particularly A. J. Strauss for many helpful discussions. This work was sponsored by the Department of the Air Force.

[1] J. C. DeWinter, M. A. Pollack, A. K. Srivastava, and J. L. Zyskind, J. Electron. Mater. **14**, 729 (1985).

[2] A. E. Bochkarev, L. M. Dolginov, A. E. Drakin, P. G. Eliseev, and B. N. Sverdlov, Sov. J. Quantum Electron. **18**, 1362 (1988).

[3] A. N. Baranov, A. N. Imenkov, M. P. Mikhailova, A. A. Rogachev, and Y. P. Yakovlev, Proc. SPIE **1048**, 188 (1989); A. N. Baranov, T. N. Danilova, B. E. Dzhurtanov, A. N. Imenkov, S. G. Konnikov, A. M. Litvak, V. E. Usmanskii, and Yu. P. Yakolev, Sov. Tech. Phys. Lett. **14**, 727 (1988).

[4] T. H. Chiu, W. T. Tsang, J. A. Ditzenberger, and J. P. van der Ziel, Appl. Phys. Lett. **49**, 1051 (1986).

[5] J. L. Zyskind, J. C. DeWinter, C. A. Burrus, J. C. Centanni, A. G. Dentai, and M. A. Pollack, Electron. Lett. **25**, 568 (1989).

[6] C-A. Chang, R. Ludeke, L. L. Chang, and L. Esaki, Appl. Phys. Lett. **31**, 759 (1977).

[7] A. Furukawa and M. Mizuta, Electron. Lett. **24**, 1378 (1988).

[8] H. C. Casey, Jr. and M. B. Panish, *Heterostructure Lasers, Part B* (Academic, New York, 1978), p. 187.

[9] C. Caneau, J. L. Zyskind, J. W. Sulhoff, T. E. Glover, J. Centanni, C. A. Burrus, A. G. Dentai, and M. A. Pollack, Appl. Phys. Lett. **51**, 764 (1987).

[10] A. Sugimura, IEEE J. Quantum Electron. **QE-18**, 352 (1982).

[11] F. Karouta, A. Marbeuf, A. Joullié, and J. H. Fan, J. Cryst. Growth **79**, 445 (1986).

[12] G. B. Stringfellow, J. Cryst. Growth **58**, 194 (1982).

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	24 September 1990	Meeting Speech

4. TITLE AND SUBTITLE
Efficient GaInAsSb/AlGaAsSb Diode Lasers Emitting at 2.29 um

5. FUNDING NUMBERS
C-F19628-90-C-0002
PE-61102F

6. AUTHOR(S)
S.J. Eglash and H.K. Choi

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Lincoln Laboratory, MIT
P.O. Box 73
Lexington, MA 02173-9108

8. PERFORMING ORGANIZATION REPORT NUMBER
MS-8696

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Systems Command, USAF
Andrews AFB
Washington, DC 20334

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ESD-TR-90-166

11. SUPPLEMENTARY NOTES
Appl. Phys. Lett. 57 (13)

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release: distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Diode lasers emitting at 2.29 μm have been fabricated from lattice-matched double heterostructures having a GaInAsSb active layer and AlGaAsSb confining layers grown by molecular beam epitaxy on GaSb substrates. For pulsed room-temperature operation these devices have exhibited threshold current densities as low as 1.7 kA/cm^2 and differential quantum efficiencies as high as 18% per facet, the highest room-temperature efficiency reported for any semiconductor diode laser emitting beyond 2 μm.

14. SUBJECT TERMS
diode lasers GaInAsSb
lattice-matched AlGaAsSb

15. NUMBER OF PAGES
3

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by AMSI Std. 239-18
298-102